

# Space Astronomy towards the Next Millennium

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## Abstract

Space astronomy allows access to wavelength regions that are not available to ground-based observatories. Collecting and analyzing radiation emitted by phenomena throughout the entire electromagnetic spectrum, the "Four Great Observatories" are performing astronomical studies over many different wavelengths and overlapping in time enabling concurrent observations. Chandra X-Ray Observatory, deployed in July 1999, will observe x-ray images and spectra of violent, high temperature events and objects to help us understand black holes, quasars, and high temperature gases. The Space Infrared Telescope Facility (SIRTF) will launch in December 2001. It is capable of observing in the near infrared, 3 – 180 micron range and provide for imaging, photometry as well as spectroscopy. The primary science themes are the detection and study of brown dwarfs and super-planets, protoplanetary and planetary debris disks, ultraluminous galaxies and active galactic nuclei, and deep surveys of the early universe. The detector arrays offer orders of magnitude improvements in capability over past infrared detectors.

Astronomical missions scheduled for 2005 and beyond are enabled through advanced technology development. The Space Interferometry Mission (SIM) will use optical interferometry technology, while The Next Generation Space Telescope (NGST) will require large, ultra-light, and deformable mirrors, and very sensitive instruments. SIM will determine the positions and distances of stars several hundred times more accurate than any previous program. This will allow SIM to probe nearby stars for Earth-sized planets. SIM will also pioneer a technique to block out the light of bright stars to take images of areas close in to the stars. NGST is to be launched in 2007 and will study how galaxies evolve, how stars and planetary systems form and evolve, and what the life cycle of matter is in the Universe.

SIRTF, SIM and NGST are part of NASA's Origins program and Chandra is part of NASA's Structure and Evolution of the Universe program. SIRTF and SIM are managed for NASA by the Jet Propulsion Laboratory (JPL), California Institute of Technology. NGST is managed by NASA's Goddard Space Flight Center and Chandra is managed by NASA's Marshall Space Flight Center.

## Introduction

This paper expands on the current and near future NASA Space Astronomy Missions as well as the plans for beyond 2005.

Space astronomy allows access to wavelength regions that are not available to ground-based observatories due to spectral absorption by the Earth's atmosphere. Continuous dark times enable space observatories long continuous exposure times. In the infrared, space based observatories provide an additional bonus in that they are free of black body radiation of the Earth's atmosphere and telescopes can be cooled down to very low temperatures, which increases the sensitivity a thousand fold for a million-fold increase in the speed of the observations. Wavelengths from gamma rays to far-infrared are available, sometimes on the same spacecraft.

## Great Observatories

The "Great Observatories", a NASA program, is a set of four large space-born observatories, designed to study the universe over many different wavelengths. The four missions are overlapping their operations phases to allow for concurrent and follow-up observations of features at many different wavelengths. The four missions that are part of the Great Observatories program are the Hubble Space Telescope (HST), the Compton Gamma-Ray Observatory (CGRO), Chandra X-Ray Observatory (CXO), and the Space InfraRed Telescope Facility (SIRTF). HST was launched in 1990 by the NASA Space Shuttle. Subsequently it has

been refurbished with a number of new instruments and capabilities. More servicing missions to HST are planned. HST observes the Universe at ultraviolet, visual, and near-infrared wavelengths. HST has contributed to understanding of the expanding universe and to determine the age of the universe to be 12 billion years. CGRO was deployed by the Space Shuttle in 1991. Its mission is to collect data on some of the most violent physical processes in the universe, characterized by their extremely energetic emissions. CXO was deployed in 1999 and is observing such phenomena as black holes, quasars, and high temperature gases in the x-ray portion of the electromagnetic spectrum. And SIRTf, to be launched in 2001, will conclude the series of Great Observatories by providing coverage in the infrared part of the spectrum.

### **Chandra X-Ray Observatory**

The Chandra X-Ray Observatory studies the violent universe, phenomena that release their enormous amounts of energy at x-ray wavelengths, temperatures that reach millions of degrees, high velocity gases accelerated by gravity to nearly the speed of light, and magnetic fields that are a trillion times stronger than the Earth's. Chandra is designed to study the deaths of stars, collision of galaxies, explosion of stars that release heavy elements from their interiors, black holes and quasars or neutron stars.

Imaging of star formations and young stars with Chandra, helps scientists understand the evolution of life on Earth. When massive stars or supernovae erupt, they release their content of heavy elements and energy into the surrounding space. Shock waves formed during this explosion due to the collision of ejecta from the supernova with the circumstellar material heat it up to 10 million degrees. Like sonic booms, secondary waves resulting from this collision further stir up the surrounding gas. The bright remnant in the center of the explosion may be a neutron star or black hole. Thus heavy elements such as carbon, nitrogen, oxygen and iron, necessary for life, formed inside the massive stars, help seed the interstellar gas, heat it with their energy of their radiation, stir it up with their force of the blast waves and cause new stars to form.

Other X-ray sources are caused by super-hot gas and dust particles that are being swallowed up by black holes. Accretion rate by quasars, due to the tremendous gravity pull, speeds up particles to form a rotating disk. Collision between particles heats them to many millions of degrees producing x-rays. The study of the x-ray energies allows the determination of the particle motion as they approach the black holes and gives scientists information about the gravity fields around black holes.

Most galaxies in our universe are grouped together in clusters. These clusters are filled with large clouds of multimillion-degree gas, held together by gravity and visible in the x-ray spectrum. However, the mass of the galaxies and gas together is not sufficient to provide the gravity to hold the clusters together. So the theory emerged that additional mass of dark matter must exist to explain the phenomena. This in fact would one lead to conclude that most of the mass of the universe may be dark matter collapsed into stars, planets and black holes that are not observable to us directly. The study of the hot gas by Chandra might shed some light on the dark matter puzzle.

Chandra was launched July 23, 1999 from Shuttle Columbia into a highly eccentric orbit with a maximum altitude of 140,000 km. The orbit is 64 hours long with 14 hours in the high radiation environment of the Earth, when the telescope instruments have to be turned off to avoid damage. The telescope is being operated from Harvard-Smithsonian Observatory, the first mission to be operated at a site other than a NASA center.

The telescope system has very specialized technology. Cylindrical mirrors have replaced normal mirrors, which would be penetrated by the x-rays. Two sets of four nested mirrors allow the incoming x-rays to ricochet off the paraboloid surface and hyperboloid surface (Figure 1) to be funneled toward the center detectors. The mirrors are made of Zeodur material with a 600 Angstrom of iridium coating to create the smoothest surfaces ever, thus allowing the x-rays to graze off its highly polished mirror surfaces. The entire telescope is wrapped in a multi-layer insulation controlling the temperature inside the telescope, preventing expansions and contractions of the mirrors and ensuring greater accuracy of the observations.

Chandra's instruments can serve both as imager or spectrometer. The High-Resolution Camera (HRC) records the x-ray images between 0.1 and 1 keV on its microchannel plate detectors. The camera is composed of two detectors, one optimized for imaging and the other optimized for spectra. The imaging field of view is 30x30 arcmin with a spatial resolution of approximately 0.5 arcsec. The HRC complements the second instrument, the Charged Coupled Imaging Spectrometer (ACIS). ACIS' two CCD arrays can provide simultaneous time-resolved imaging and spectroscopy of up to 50 different energies within the range of 0.2 and 10 keV. The imaging field of view is 16x16 arcmin. In order to gain even more energy information, two screen-like instruments, called diffraction gratings, are inserted between the telescope and the detectors. The gratings change the path of the x-rays, depending on its color or energy, and the x-ray camera record the color and the position. The High Energy Transmission Grating (HETG) is used with the ACIS on high to medium energies ranges of 0.5 to 10 keV with a spectral resolution,  $E/\Delta(E)$  ranging from 60 to 1000. The Low Energy Transmission Grating (LETG) is being used in conjunction with the HRC, dispersing low energies from 0.08 to 6 keV, with a resolution of 30 to 2000. The study of such a large variety of energies in the x-ray spectrum enables scientists to determine the composition of the objects emitting the radiation and learn about their evolution.

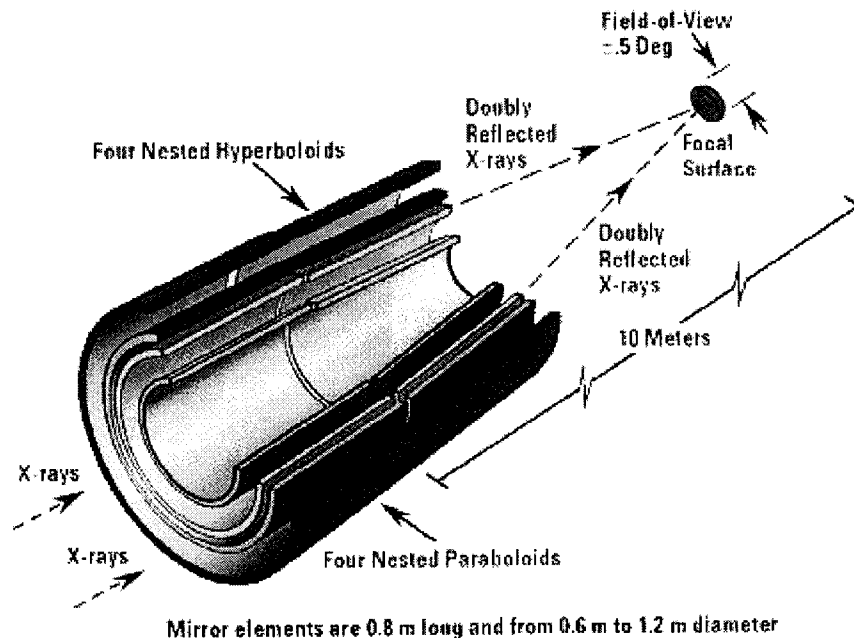


Figure 1. Chandra's special mirror configuration.

### Studying the Universe in the Infrared – Space InfraRed Telescope Facility

Most objects in the universe, such as cool stars, planets, interplanetary dust, interstellar gas and the universe itself are too cool to emit visible light, but they do emit in the infrared. Interstellar dust that shrouds the center of galaxies and clusters is totally opaque in the visible and ultraviolet, but becomes mostly transparent in the infrared, allowing scientists to study regions of star formation. The expanding universe has objects in the distant universe that move away from us. This cosmic expansion shifts the light from distant galaxies into the infrared. SIRTf, a cooled meter-class telescope, with background limited detectors and multiple instruments, is going to offer substantial improvement over past and existing capabilities.

Some of the scientific themes to be pursued by SIRTf are identified below and are expected to greatly contribute to our understanding of these phenomena.

- 1) Objects such as brown dwarfs and super planets have too little mass to ignite the fusion reactions of true stars, but they are larger and warmer than planets found in our solar system. SIRTf will allow

detection and characterization of the abundance of these objects which can be found in the halo of galaxies and in young star clusters, contributing to the understanding of the dark matter that is thought to exist in the universe. In addition spectroscopy will contribute to the determination of their nature and composition.

- 2) The properties and interrelationships of comets, asteroids, interplanetary dust and other small bodies in the Solar System are to be investigated by SIRTf. The structure and composition of disks of debris and dust surrounding nearby stars may be an indicator of solar system formation. SIRTf will be able to trace the evolution of these formless clouds of dust and gas into a mature solar system like ours. By comparing low resolution spectra of the disk material with emission spectra from comets, SIRTf provides comparisons of the primitive solar system, of which comets are thought to be remnants, with those of the debris disks around other solar systems.

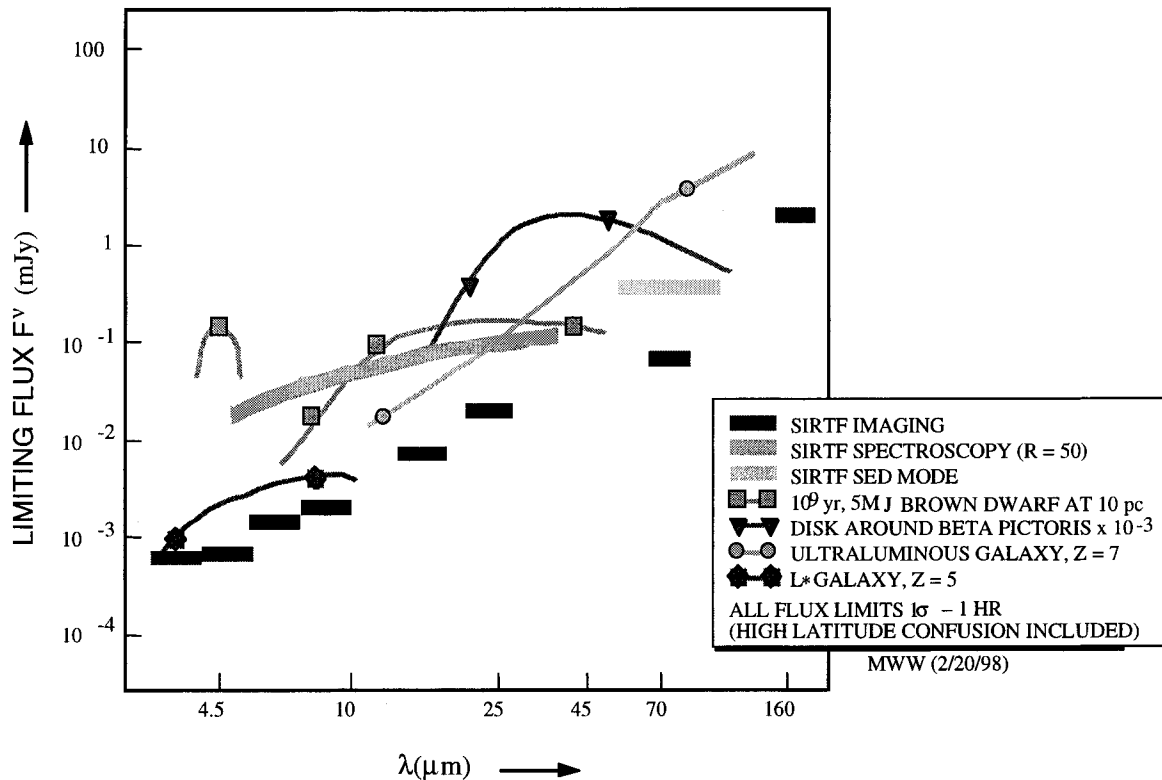


Figure 2. SIRTf Sensitivity

- 3) The study of the physical processes which power the Ultraluminous Galaxies, which are at the core of intense bursts of star formation, stimulated by colliding galaxies and the probing of dust enshrouded quasars and active galactic nuclei powered by black holes, will be at the center of SIRTf's inquiry. In addition spectroscopy will be able to establish the source and abundance of heavy metals detected in the red shift.
- 4) Deep surveys of the distant and early Universe will be explored at red shifts greater than 3. SIRTf is expected to discover thousands of galaxies per square degree on the sky.
- 5) In addition to these themes, SIRTf is also part of the *Origins* Program, which seeks to understand the origins of the Universe, galaxies, stars and planets. Thus SIRTf will address a wide range of astronomical investigations, including studies of the outer Solar System, the early stages of star formation, and the origin of chemical elements.

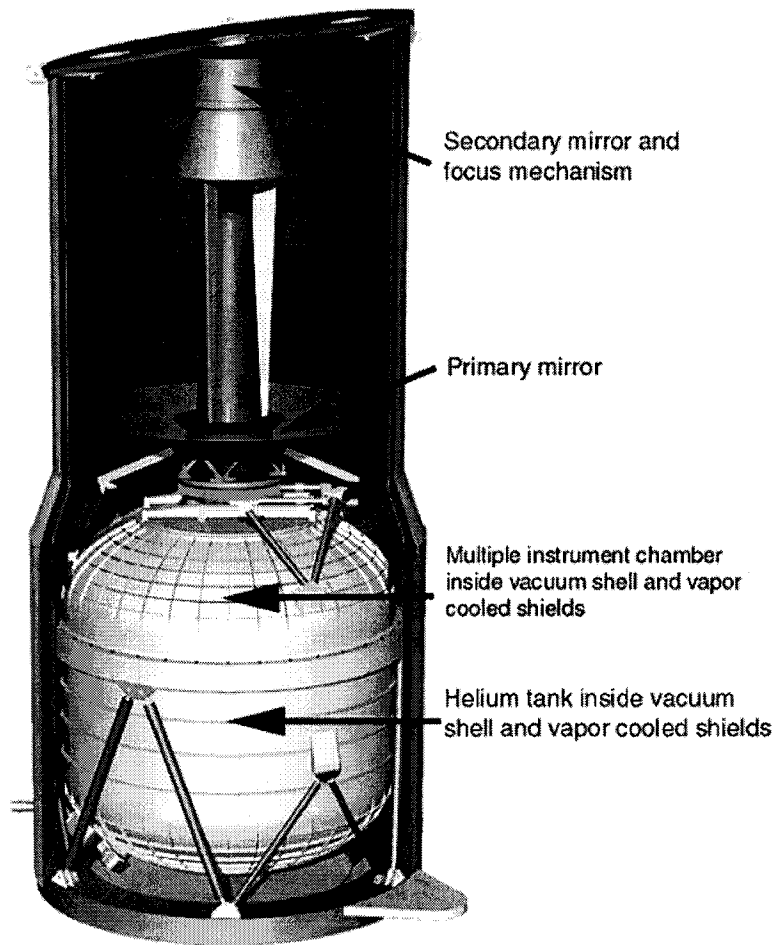


Figure 3. SIRTf Warm Launch Architecture.

SIRTf will be launched in December 2001 into an Earth trailing heliocentric orbit, drifting away from Earth at a rate that bring it out to .64 AU in 5 years. This orbit is favorable for both mass and thermal reasons and has considerably helped simplify and reduce the development cost of SIRTf. The solar orbit provides such important advantages as elimination of occultations and eclipses providing continuous sky access and excellent visibility.

SIRTf has taken advantage of considerable infrared detector technology improvements brought about by industry, which served military interests in developing detectors for high-background temperature environments in wavelengths shorter than  $30\mu\text{m}$ . Astronomers have adapted this technology for low-background and high sensitivity sky observations in the infrared up to  $200\mu\text{m}$ . Thus SIRTf will feature a thousand-fold increase in sensitivity. The size of the arrays has increased many thousands of times as well. The benefit of this detector revolution is that observations can now be accomplished in very short integration times considerably increasing the observatory's efficiency. SIRTf features three instruments, which provide imaging, photometry and spectroscopy over wavelengths ranging from  $3.6\mu\text{m}$  to  $160\mu\text{m}$ . Figure 2 shows the limiting flux as a function of wavelength, an indication of how faint an object SIRTf is able to observe with its complement of detectors

SIRTf will be launched at ambient temperature and allowed to radiatively cool in space. Only the instrument detectors and the compact cryostat are encased in a vacuum shell sitting on top of 360 liters of superfluid helium tank that cools the instrument chamber. (Figure 3) Within one week of passive cooling

the temperature of the observatory outer shell has fallen to  $\sim 50$  °K. The helium boil-off will further cool the inner telescope assembly including the instruments down to 5.5 °K. The liquid Helium bath will serve as a heat sink and remain at 1.5 °K. The outer shell temperature will reach  $\sim 33$  °K.

### NASA's Origins Program.

The *Origins* program is a NASA program that looks into the next millennium and defines the high-level exploration goals between 2000 and 2015. *Origins* program seeks to understand the origins of the Universe, galaxies, stars and planets. How did galaxies form in the early universe and what role do galaxies play in the appearance of planetary systems and life? How do stars and planets systems form and are there life-sustaining planets around other stars? How did life originate on Earth and does it exist elsewhere in the Universe?

These three leading questions have led to the definition of a number of mission objectives, which drive the astronomy missions for the new millennium.

- 1) The new millennium missions seek to understand the role gravity plays in the emergence of galaxies from the smooth particle distribution of the early Universe. These missions study the birth and aging of a galaxy and how this process influences the chemical composition of stars, planets, and living organisms. Next Generation Space Telescope (NGST) mission will be designed to achieve this goal.
- 2) A number of missions such as NGST, Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF) will be looking for planetary systems around young stars and for life sustaining planets around other stars close to our solar system.
- 3) Rovers, aerobots and in-situ instruments will be designed to study how life arose elsewhere in the solar system and beyond. Bioastronomy will investigate if life exists elsewhere in the Universe and draw parallels from life on Earth.

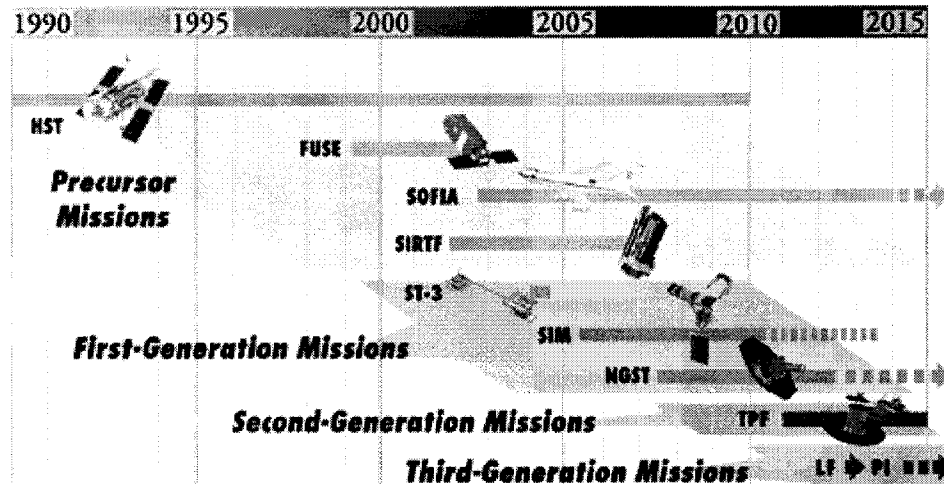


Figure 4. *Origins* Timeline

The technological feat to accomplish the *Origins* science goals is enormous. The timeline (Figure 4) shows how chronologically the missions are grouped in order of increasing technological challenge. The **Precursor** missions, which SIRTIF is part of, are technologically very challenging but they are well along in their development and/or have become operational. The **First Generation** missions require revolutionary new technologies that are currently under development. These include much larger but lighter optics and collections of telescopes that together make images sharper than very large telescopes. These missions will be launched after 2005. SIM and NGST are part of this group of missions. They are part of

technology pathfinders to the **Second Generation** missions. TPF is currently the only mission planned in this latter category and will be launched after 2010. And finally the **Third Generation** missions will have to deal with such an enormous technological challenge that at this point these missions are only a vision. Planet Imager (PI) is the only mission planned in this category in the time frame after 2015.

### The Space Interferometry Mission.

SIM is a space based optical interferometer for precision astrometry. The design is a 10-meter baseline, Michelson beam combiner to be launched mid-2005, for a minimum 5-year mission lifetime. SIM will be performing global astrometry, local astrometry, synthesis imaging and will demonstrate the new technology of fringe nulling for future missions. SIM will be observing in the band-width between 400 and 1000 nm. The expected all-sky astrometry accuracy to be achieved by end of mission is  $4 \mu\text{s}$ . SIM will measure the proper motion by parallax with an accuracy of  $2 \mu\text{s}/\text{yr}$  and the narrow-angle astrometry accuracy is expected to be  $1 \mu\text{s}$  in one hour for objects at a distance of 10 pc.

The primary science objectives of SIM are to search for planets around stars within 150 pc, measure distances to stars throughout the Galaxy and demonstrate fringe nulling technology for future interferometry missions. The following science investigations are enabled by this mission:

- 1) Search for astrometric signature of planets around nearby stars.
- 2) Measure distances to spiral galaxies using rotational parallaxes
- 3) Study the mass distribution in the halo of our Galaxy
- 4) Observation of the dynamics of our local group of galaxies
- 5) Determination of the spiral structure of our Galaxy
- 6) Calibration of the cosmic distance "ladder"
- 7) Determination of the ages of globular clusters
- 8) Observation of the internal dynamics of globular clusters
- 9) Measurements of the masses and distances to MACHOs
- 10) Determination of accurate masses for low-mass stars in binaries
- 11) Imaging of emission-line gas around black holes in active galactic nuclei
- 12) Imaging of dust disks around nearby stars through nulling.

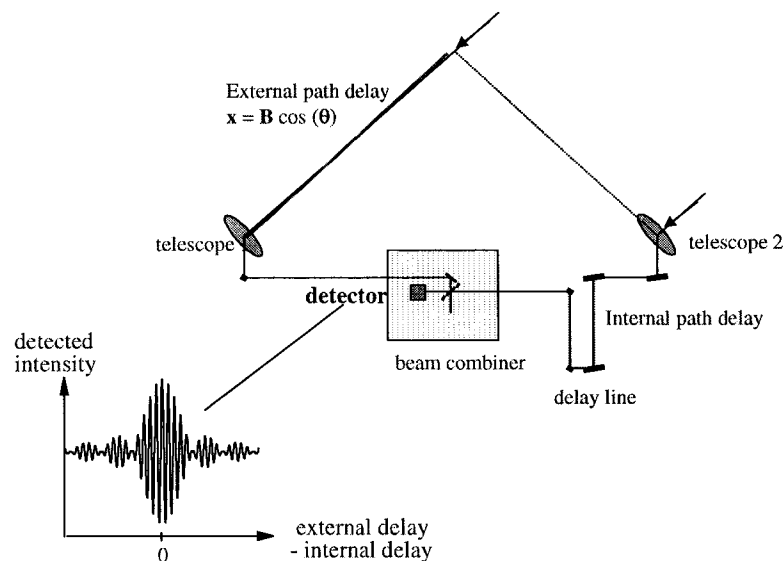


Figure 5. SIM Astrometric Measurement -  
White light fringe position measures one coordinate of star position.

Figure 5 illustrates the SIM interferometer, composed of two collectors located at each end, an internal delay line and a beam combiner to interfere the starlight arriving from each interferometer arm. As the starlight enters the collectors it is sent toward the beam combiner in order to form white-light fringes, which occurs when the optical path traversed through the left arm is equal to the right arm. An optical delay line is added to one arm in order to shorten or extend the optical path as needed, until they are equal. Knowing the exact delay distance, and the exact distance of the baseline, the determination of the angle to the star is made.

However, in order to measure distances between stars, the space-based platform needs to remain stable at the  $\mu\text{s}$  level. This presents a major challenge when observing dim targets, which require very long integration times. Two additional interferometers (Figure 6) are added to determine the orientation of the baseline vector – called guide interferometers – and observe a pair of bright stars while the science interferometer observes a number of science targets. The spacecraft attitude control system senses from the guide interferometers the changing baseline orientation and corrects for its movement during the science observation period. White fringe acquisition and measurements will be limited by the changes in attitude of the spacecraft but also by the on-board disturbances which vibrate the elements in the optical system. An internal metrology system monitors the optical path vibrations. The laser metrology will feed data to the spacecraft, which will autonomously command the delay line to a position, which stabilizes the optical path of the science star. Together the external baseline metrology and the internal metrology allow sufficient stabilization for long science target integration times.

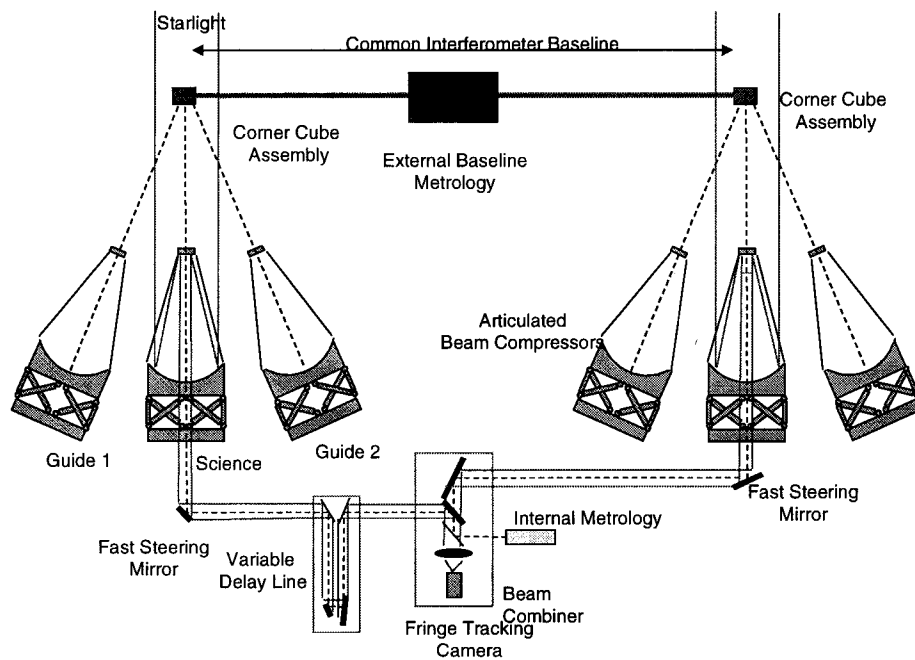


Figure 6. SIM Optical Layout – Triple Interferometer

Measuring the angle to a distant star from two vantage points (figure 7) allows the determination of the parallax angle  $\pi$  and the distance ( $D = 1/\pi$  parsec) to that star. The bigger the baseline, the better the accuracy of the measurement. Knowing the distance to stars in turn provides input to determine the brightness of the star. From this in turn we can determine something about the chemical composition and evolution of the star. Using parallax SIM will measure distances to 25 kpc to an accuracy of 10%. SIM will also determine distances to star clusters up to 130 pc, the galactic center at 8.5 kpc and the large Magellanic cloud at 50 kpc.



A grid catalog made up of quasars and other bright distant stars will be established. Science observations are accomplished using these reference grid stars. Distances to spiral galaxies are performed using rotational parallaxes and ground based radial velocity measurements allowing the astrometric measurement of galactic rotation. 3-D motions of a large sample or cluster of stars can thus be studied, their mass distribution determined, and information about formation and evolution deduced. Using stellar velocities the size, mass distribution and dynamics of our galaxy is studied. The method to search for planets around other stars uses the astrometric detection of wobble due to gravitational tug of unseen planets. Earth-mass planets signature is 1650 times smaller than Jupiter size planets and is detectable only around the nearest stars at 10pc away.

As a conclusion, SIM will serve as a technology precursor for future interferometers in space. In addition to unprecedented science return, it will demonstrate the operation of a Michelson interferometer in space, fringe nulling technology, control of thermal and vibration environment, synthesis imaging in space, precision deployment and angle and pathlength control.

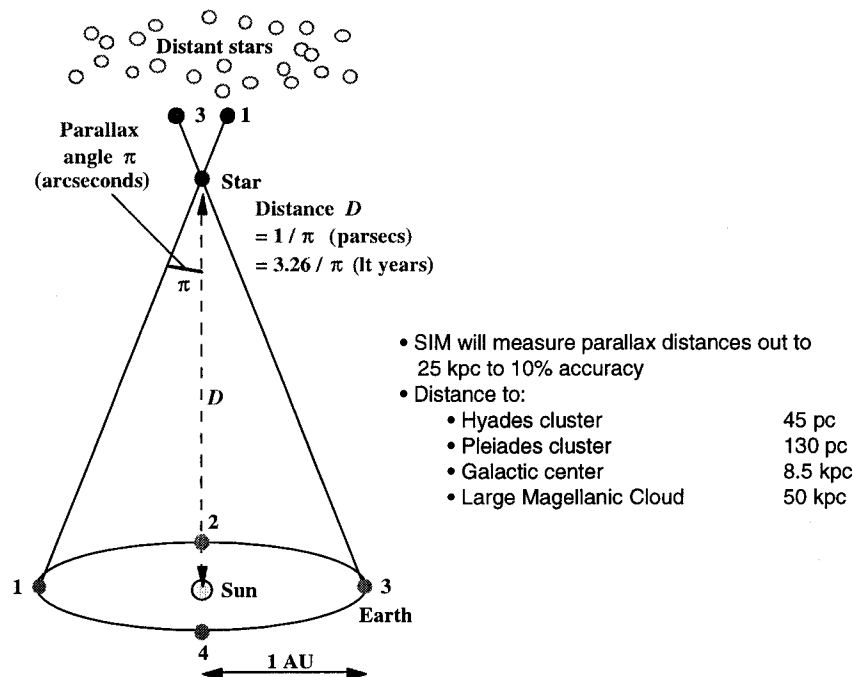


Figure 7. Measuring Distances in the Galaxy

### Next Generation Space Telescope (NGST)

HST and confirmation from CGRO, have established the age of the universe at 12 billion years. Telescopes have been peering farther and farther back in time and space to study objects from the earliest universe. HST discovered that galaxies had already formed 5 billion years after the big bang. The Cosmic Background Explorer (COBE) looking back as far as 1 to 100 million years from the big bang, shows only very slight differences in the density of matter, differences which are believed to have led to the formation of larger structures such as galaxies. NGST will be designed to investigate the time 1 billion years from the big bang, a time when primordial matter began to form into galaxies and stars.

NGST's science objectives are to study the birth of the first galaxies, the formation of stars and planets, the shape and evolution of the universe, the chemical evolution of the universe and the nature of dark matter. The target objects for these studies are deep fields, the universe at redshifts beyond  $z > 2$ , supernovae, stellar populations, cosmic distances and objects from the Kuiper Belt. Flux densities of these observations are in the range of nanoJanskys - Figure 8. (By comparison SIRTf observes fluxes in the microJansky)

These major science drivers have led to technology requirements for very large apertures, (ultralight 8 m deployable telescope) infrared capabilities, (cryogenic optics and radiatively cooled telescope) and very large detector arrays observing in the range from 0.5 to 30  $\mu\text{m}$  with a cosmic background limited sensitivity. Due to limited integration & test on the ground of these very large structures, but keeping operations costs manageable, the mission and flight design must lend themselves to ease and flexibility of operations. The technology breakthroughs required for NGST have put its launch after 2008. The mission lifetime goal is up to 10 years.

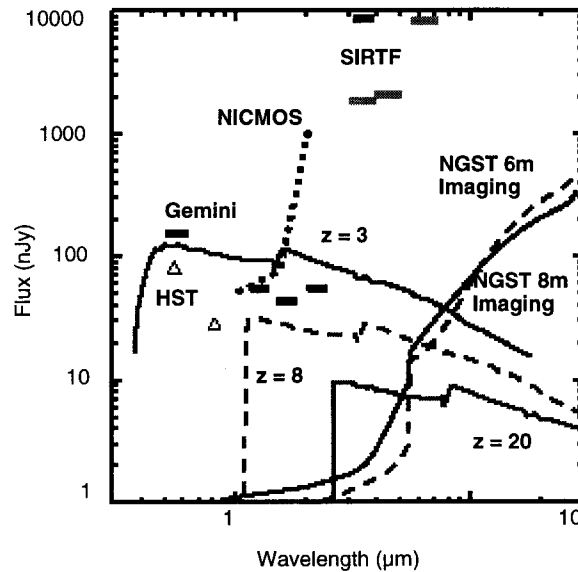


Figure 8. Projected NGST Sensitivities - 10000 sec. Exposure,  $S/N = 10\sigma$ ;  $\lambda/\Delta\lambda = 3$

As is the case for all advanced NASA missions, the development strategy for NGST is to establish the main science design drivers and determine the technology requirements to implement those drivers. Based on available industry technology, heavily leveraging of military spin-offs and with new NASA funded stretch technologies, a detailed technical, cost and science trade is performed. From this trade study emerges a cost driven implementation plan and technology roadmap. More and more frequently international or other agency contributions are included in the mission trade space to make the mission feasible.

The technology roadmap becomes the critical path for the mission. Rapid prototyping shows the feasibility of key technologies required for the mission. A robust pre-development technology program with well-defined technology milestones is the next essential step. Ground testing and flight technology demonstrations validate the new technology. And finally the technology if successfully validated in flight is used to develop the ambitious science mission. The lead-time for this mission is very long and NGST is planned to be launched after 2008.

## Conclusions

The *Great Observatories* are leading the astronomical discoveries into the new millennium. They serve as scientific and technologic precursors to the much more ambitious missions under development for the *Origins* program, whose quest is to study the origins of the universe, galaxies, stars, planets and life itself. Challenges for those missions are many orders of magnitude larger and they are crucially dependent on the successful technology roadmap paving their future. Keeping the precarious balance between technological advances and mission simplicity is the great challenge coming with a bold science program.

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